

# High Power 938nm Cladding Pumped Fiber Laser

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# High Power 938nm Cladding Pumped Fiber Laser

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## ABSTRACT

We have developed a Nd:doped cladding pumped fiber amplifier, which operates at 938nm with greater than 2W of output power. The core co-dopants were specifically chosen to enhance emission at 938nm. The fiber was liquid nitrogen cooled in order to achieve four-level laser operation on a laser transition that is normally three level at room temperature, thus permitting efficient cladding pumping of the amplifier. Wavelength selective attenuation was induced by bending the fiber around a mandrel, which permitted near complete suppression of amplified spontaneous emission at 1088nm. We are presently seeking to scale the output of this laser to 10W. We will discuss the fiber and laser design issues involved in scaling the laser to the 10W power level and present our most recent results.

## 1. INTRODUCTION

It has long been a challenge to achieve high power laser or amplifier operation of the  ${}^4F_{3/2}$ - ${}^4I_{9/2}$  transition of neodymium based laser media because of the 3-level nature of the transition and competition from the  ${}^4F_{3/2}$ - ${}^4I_{11/2}$  4-level transition. Multi-watt operation on this transition has recently been achieved in crystal hosts such as YAG and YVO<sub>4</sub> [1]. However, laser or amplifier operation of the  ${}^4F_{3/2}$ - ${}^4I_{9/2}$  transition in glass hosts or optical fiber hosts to date has been limited to power ranges on the order of 100mW [2]. Silica glass hosts offer many advantages over their crystal counterparts, such as broader tuning ranges (900nm to 950nm) and for specific material composition, more favorable branching ratios for the  ${}^4F_{3/2}$ - ${}^4I_{9/2}$  transition [2]. Optical fiber hosts also offer the potential of using wavelength dependent bend induced losses to create a distributed filter to suppress laser action on the  ${}^4F_{3/2}$ - ${}^4I_{11/2}$  transition [3]. We are developing this amplifier as a 938nm source for sum-frequency mixing with a 1583nm high power erbium fiber laser to achieve high power 589nm light for guide star applications for astronomy [4].

## 2. 938nm CHALLENGES

There are a number of challenges to be overcome in order to get high power operation of the  ${}^4F_{3/2}$ - ${}^4I_{9/2}$  transition in an optical fiber. Because the desired 3-level transition is competing with an undesired 4-level transition, pumping to transparency guarantees large gain in an undesired wavelength band. Further, cladding pumping, the standard method for achieving high output power from a fiber laser or amplifier is not intrinsically compatible with 3-level laser systems as the pump and signal beam do not have high overlap and thus it is difficult to achieve high inversion in the laser media. However, the materials with the best branching ratios (nearly pure fused silica) are also the ones into which neodymium is the least soluble. This increases the attractiveness for an optical fiber host due to the potential of long interaction lengths, which are preferred for low doping concentrations.

Of particular concern is the neodymium concentration level at which significant quenching occurs. We obtained several samples of standard neodymium-doped optical fiber with varying concentrations for characterization for use in our amplifier. The samples were co-doped only with germanium to maximize the branching ratio into the desired transition [2]. We were also able to obtain samples of the preforms from which these fibers were drawn. Using the preform samples we measured the upper state lifetime of the laser transition. In all samples, we found there was a 0.4-0.8 $\mu$ s component (due to quenched sites) and a 470 $\mu$ s component (due to active sites). By comparing the relative strengths of

these components we were able to estimate the percentage of ions that were quenched or not likely to contribute to the gain. A second measurement of small signal absorption at 905nm and small signal gain at 905nm with nearly complete inversion (achieved by pumping a short length of fiber in the core with 650mW of 830nm pump light from a Ti:Sapphire laser) was made on the optical fibers. This measurement followed the techniques used by Giles to characterize rare earth doped optical fibers for modeling [5] and permitted an independent estimate of the number of quenched sites. The second measurement also permitted us to understand the gain and absorption spectrum of our fiber samples. The results of the quenching measurements are plotted in figure 1 below.

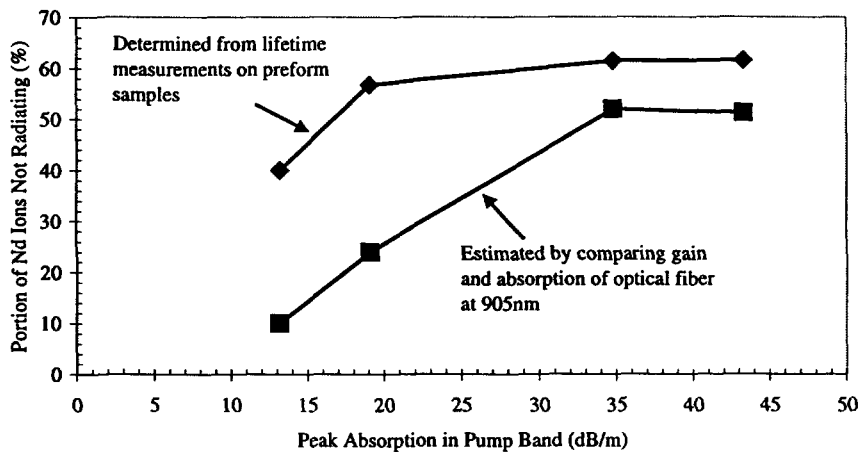


Figure 1: Estimate of Nd ion quenching in germanium codoped silica fiber samples as a function of peak absorption in the pump band.

In figure 1, one observes the optical fiber and the preform from which it came have the same general trend with respect to quenching vs. concentration. However, it appears, the optical fiber as drawn shows significantly better performance than would be expected from the preform measurement alone. We speculate that the effect of quenching during the fiber draw improves the distribution of neodymium ions in the lattice and thus reduces the number of quenched neodymium ions.

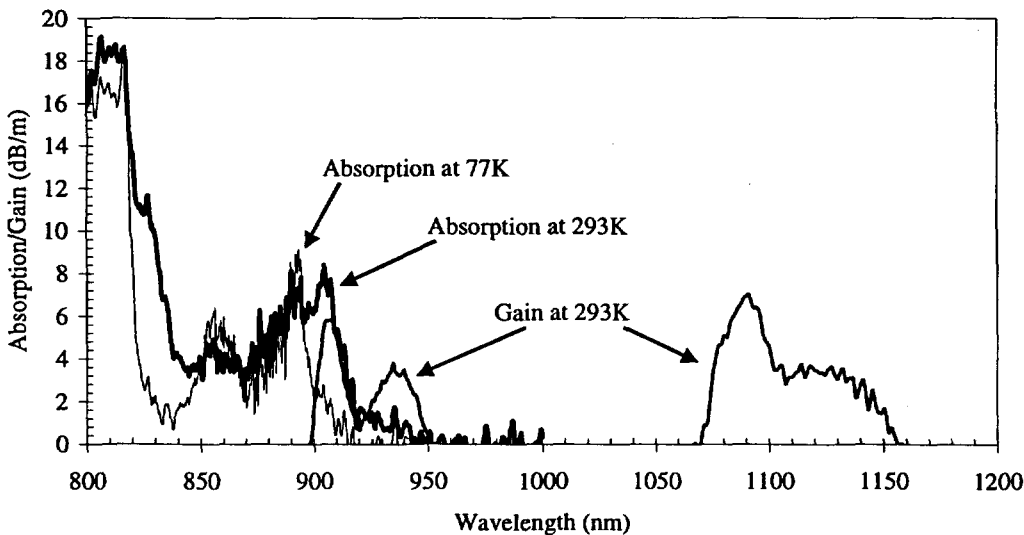


Figure 2: Absorption of a Nd-doped fiber with quenching at room temperature and 77K and gain at room temperature.

In figure 2, typical absorption and gain spectra for the fibers are plotted. Data below 800nm has been suppressed. Because, the fiber core is not single mode below 800nm there were unacceptably high errors in the data in that region. We have also measured the fiber absorption at 77K. The absorption in the 920nm-950nm region, of particular interest to our application, is virtually eliminated at 77K. Thus, the transition is effectively a 4-level transition when the fiber is cooled, making it much more compatible with cladding pumping. Liquid nitrogen cooling of a bulk laser gain media, would be difficult to achieve in a practical laser application. However, the fiber amplifier is much better suited to immersion in liquid nitrogen as it can be coiled and bent easily. This provides for a simple and robust means to isolate the remaining amplifier components such as the coupling optics for the signal and pump beams from the 77K temperatures. A fluorinated glass pump cladding ensures the guiding properties of the optical fiber would operate essentially the same at 77K as at 293K.

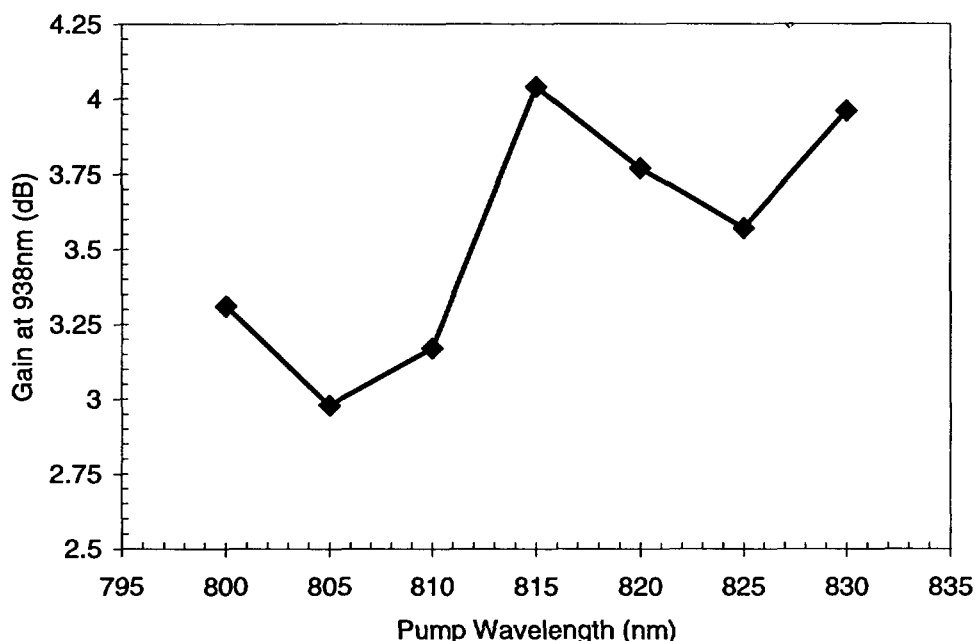


Figure 3: Gain at 938nm vs. pump wavelength for constant absorbed pump power.

We measured gain vs. pump wavelength for a short (~1m) piece of Nd fiber that was core pumped at room temperature (figure 3). Intriguingly, at a pump wavelength around 815nm the gain at 938nm suddenly jumps upwards. This is consistent with changes in the absorption spectra as a function of concentration, which show a distinct peak at 816nm emerging as the Nd concentration is lowered. This suggests that the unquenched Nd ions have a spectra that is different and distinct from the quenched Nd ions. This implies that while it may or may not be practical to reduce the Nd concentration sufficiently to completely eliminate quenching, it may be possible to mitigate the impact of quenching via careful pump wavelength selection.

As mentioned above, the 1088nm transition is a 4-level laser transition and the 938nm transition is 3-level. These transitions are competitive, with the 938nm transition having an obvious disadvantage due to its 3-level nature. For cladding pumping, this disadvantage is exaggerated. For our case, we constructed a cladding pumped fiber with a 0.22NA, 200μm pump clad and a singlemode 7.5μm core with absorption and gain spectra as detailed in figure 2 above. A 200m piece of this fiber would absorb most of the light in the pump cladding. If we use our measured gain and absorption spectra at 77K, 195K (this was not shown in figure 2) and 293K and an effective inversion approximation, we can estimate the gain at 1088nm for a constant 16dB gain at 938nm as a function of temperature. This estimation is detailed in table 1 below.

	77K	195K	293K
Average Inversion	0.0229	0.1006	0.212
938nm Gain (dB)	16.03	16.02429	16.016
1088nm Gain (dB)	31.602	138.828	292.56

Table 1: Theoretical estimate of gain at 938nm and 1088nm vs. temperature.

We see that at room temperature, our cladding pumped amplifier has little to no hope of being effective at 938nm, due to extremely high gain at 1088nm. At 195K (dry ice sublimation), the situation is improved, but still extremely bad. At 77K, the 1088nm gain is still high, but there is some hope of introducing compensating losses at 1088nm that will permit preferential operation at 938nm. We also note that operation at 77K “freezes out” any quenched ions that may have absorption at 938nm.

The issue of gain competition from the 1088nm transition remains, however. Most optical fiber amplifiers are coiled, by choosing the appropriate bend radius for the coiling we can create high loss at 1088nm with minimal losses at the 938nm signal wavelength. To understand this better, we measured the bend losses of the fiber at 938nm and 980nm and compared them to losses expected from theory [6]. We also used the theoretical expressions to what the losses would be at 1088nm. These results are shown in figure 4 below.

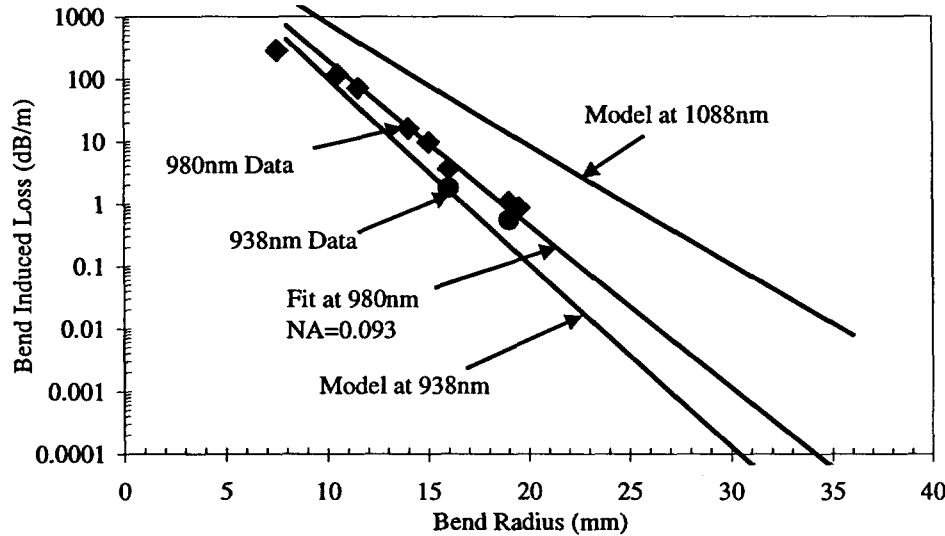


Figure 4: Measured bend loss (dB/m) as a function of bend radius (mm) for 980nm and 938nm (points). A bend loss model has been fit to the data (lines). The fiber numerical aperture was used as a fit parameter and a value of 0.0932 was found to provide the best fit. An independent measurement of the numerical aperture from the manufacturer found a value of 0.09.

For ~24mm bend radius, it appears from the plot above that we could generate >200dB of loss at 1088nm with less than 2dB of induced loss at 938nm for a 200m long fiber. What is not shown however, is that the pump cladding we employed also experienced losses upon coiling, which limited the effective bend radius we could use for coiling the entire fiber to >35mm. To overcome this issue, we chose to induce bend loss at one end of the amplifier and pump from the other end. We close this section by noting that future work will explore fiber designs that permit 938nm cladding pumped fiber amplifiers to operate at room temperature.

### 3. SYSTEM DEMONSTRATIONS

Utilizing the knowledge from our investigations of the Nd doped optical fiber, we have constructed a master oscillator, power amplifier system configuration using cladding pumped Nd doped fiber amplifiers. Our amplifiers were cooled to

77K and had lumped bend losses at the input to suppress 1088nm parasitics. A schematic of the system is shown below in figure 5.

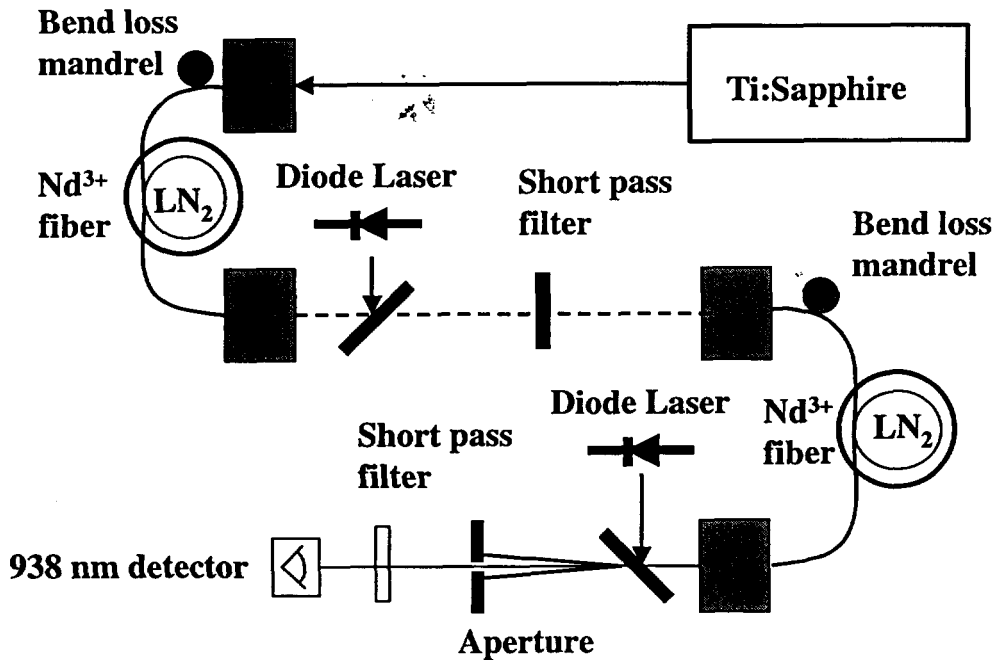


Figure 5: Schematic of the 938nm cladding pumped optical fiber system.

In figure 5 above, a two-stage amplifier configuration was employed to maximize the output power of the amplifier. The same type of fiber was used in each stage. The fiber was 100m long in the first stage and 200m long in the second stage. The core of the fiber employed had loss and gain characteristics as measured and reported in figure 2 and bend loss characteristics as reported in figure 4. The active fiber had a fluorinated outer region providing a 0.22NA, 200 $\mu$ m diameter pump cladding. The core had a neodymium doped germano-silicate material composition and was 7.5 $\mu$ m in diameter with an NA of 0.09. A peak small signal pump wavelength absorption of 19dB/m at 810nm was measured for light propagating in the core of the fiber. A short pass filter was employed between stages of the amplifier to eliminate amplification of 1088nm ASE from the first stage in the second stage. The 938nm signal power and 1088nm parasitic powers were determined by measuring the output power of the fiber at the power meter with and without the short pass filter and employing knowledge of the loss of the filter at 938nm and 1088nm. The bend mandrels employed were 19mm in radius and 10turns of fiber was wound onto each mandrel. 25W 808nm LIMO laser diodes were employed for the pumps. In the case of the 100m long amplifier, there was a significant amount of transmitted pump light. A Ti:Sapphire laser was used as the master oscillator. The Ti:Sapphire had an output power of around 500mW, good beam quality and a large effective linewidth, such that stimulated Brillouin scattering was not a system issue, despite long fiber lengths and high optical powers. An aperture at the output prevented cladding light from the fiber from striking the power meter. The output power from the second stage amplifier at 938nm and 1088nm is shown in figure 6 below.

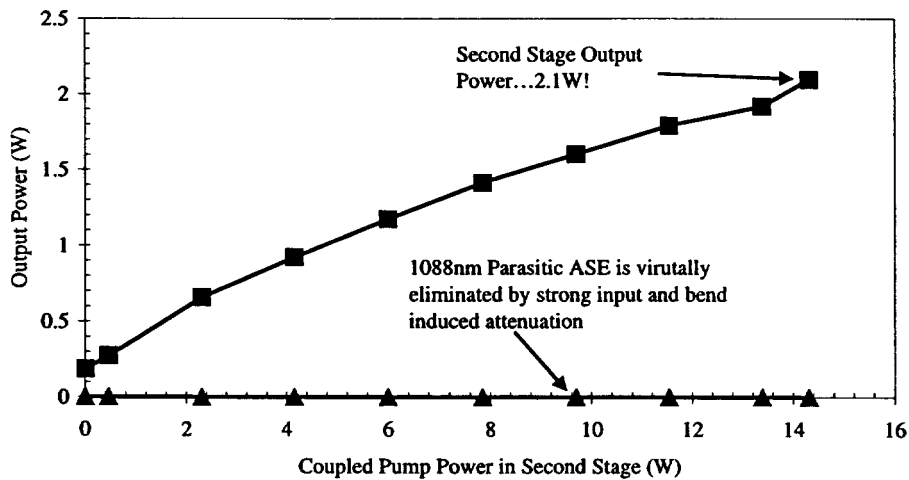


Figure 6: Output of 938nm amplifier system.

We note above that the total coupled pump power was only about 14W. There were significant losses in the dichroic mirrors we employed to combine the pump and signal wavelengths and the coupling optics were also not optimized. An additional 10W of coupled pump power would have brought the output power up to closer to 3W! We also note that the amount of observed parasitic power at 1088nm was minimal on the scale of the output power of the 938nm light. For configurations in which no bend loss was employed, we observed 1088nm output power greater than that observed at 938nm.

As discussed in the introduction, our goal in developing the 938nm laser system is to sum-frequency mix it with a high power 1583nm lasers system in order to generate 589nm light for laser guidestar applications. We have done so, using two fiber lasers as shown in the schematic in figure 7 below.

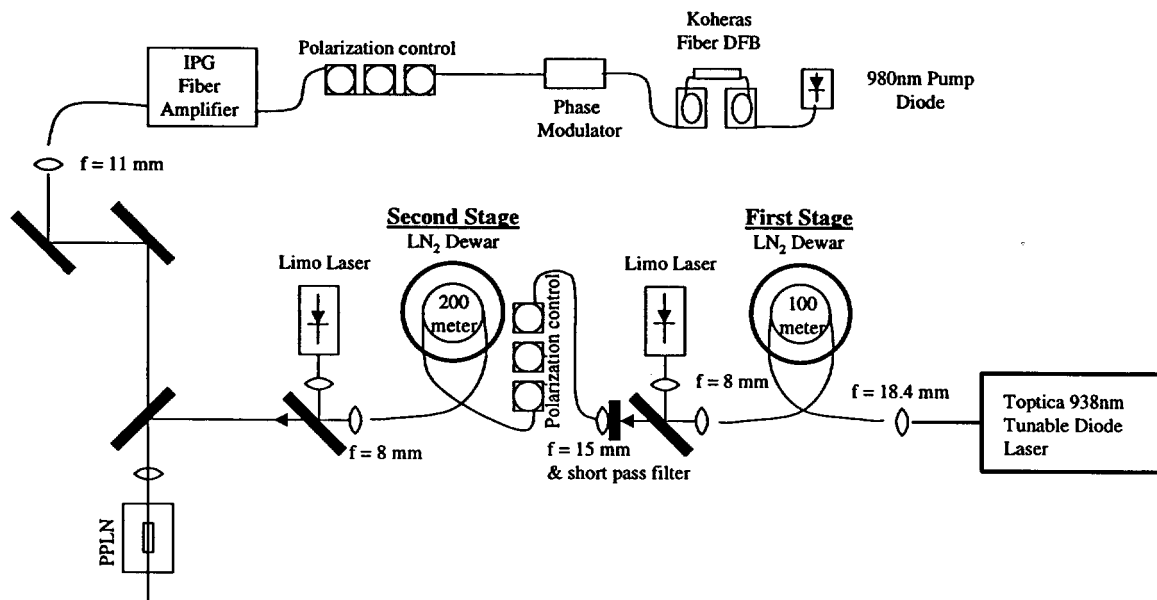


Figure 7: Schematic of the 589nm fiber laser source.

In figure 7 above, our 1583nm laser system was built entirely of commercially available components and consisted of a Koheras fiber DFB laser master oscillator with an output power at 1583nm of about 3mW. This light was passed through a phase modulator, which increased the bandwidth to about 100MHz. The light then went into a 10W IPG L-Band erbium doped fiber amplifier. The output power of this system was measured to be 10W at 1583nm when the amplifier was turned fully on. For the sum frequency mixing experiments, however, the amplifier output was limited to about 2W. The 938nm system configuration was essentially the same as that described in figure 5 above. The exception being that the Ti: Sapphire laser was replaced with a Tuionics 938nm external cavity laser diode, with an internal tapered semi-conductor laser that could put out up to 400mW of 938nm light with a noise broadened bandwidth of about 500MHz. Due to the reduced 938nm input power and poorer beam quality resulting in poorer fiber coupling, the revised system had a 938nm output power less than 1W for the sum-frequency mixing experiment. Nevertheless, when the 938nm light was combined in the PPLN (5cm long crystal, 9.45 $\mu$ m period) with the 1583nm light, we observed a strong 589nm output. This is shown in figure 8 below, where we have plotted 589nm output vs. PPLN crystal temperature.

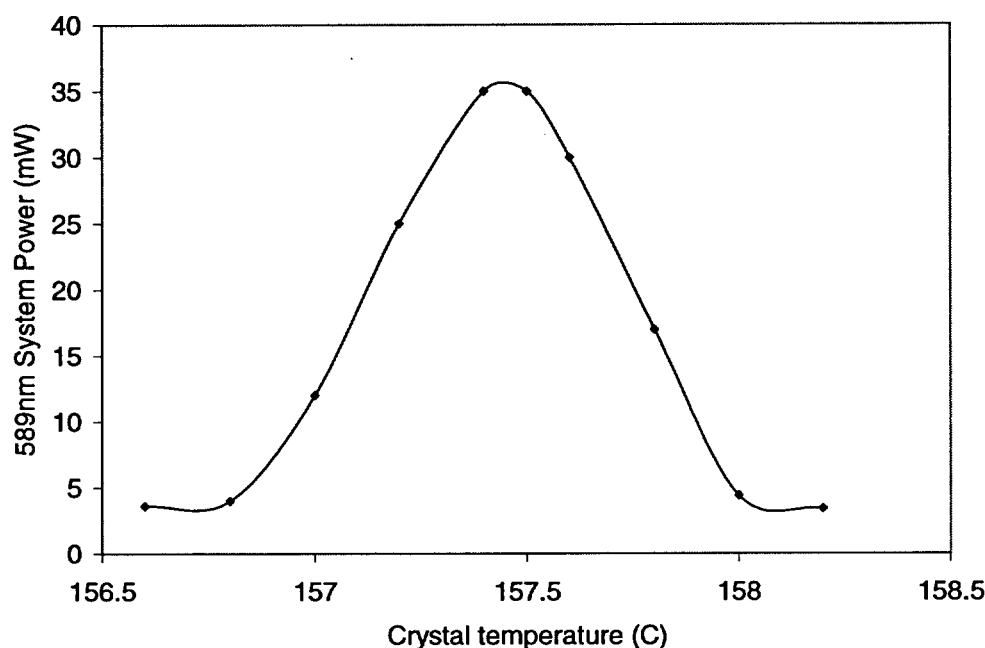


Figure 7: 589nm output power from fiber laser sum-frequency mixing vs. PPLN crystal temperature. Input power was 2W at 1583nm and 0.7W at 938nm.

We are working to improve the performance of the 938nm system using the Tuionics laser diode, which should permit much higher 589nm output powers.

#### 4. CONCLUSIONS

While an impressive result of 2.1W of output power at 938nm has been obtained, much can be done to improve this result in future design iterations. In particular, understanding of the quenching of neodymium sites was not complete until after the cladding pumped fiber had been obtained. A fiber with small signal absorption of 10dB/m at 810nm would suffer much less from pump losses due to quenching according to the data presented in figure 1. Furthermore, the amplifier fiber in question was much longer than desired resulting in high passive losses due to high scattering out of the fiber core, which is typical in rare earth doped optical fibers. We are presently redesigning our amplifier fiber to minimize quenching and passive losses, which should improve both the amplifier output power and efficiency and

reduce its length and corresponding susceptibility to stimulated Brillouin scattering. We are also seeking to eliminate the bend induced loss in the pump cladding, which will permit smaller bend radii to be employed across the entire amplifier and thus increase the amount of loss at 1088nm, while minimizing the loss at 938nm. We believe the combination of these re-design efforts will result in a system capable of operation at 10W of output power at room temperature.

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